A cross-linguistic investigation of articulatory coordination in word-initial consonant clusters

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1 Introduction

This paper is a preliminary report on a series of experimental investigations of articulatory coordination in word-initial consonants in a variety of languages. These experiments were designed, conducted, and analyzed in the context of a Linguistics graduate seminar on syllable structure taught at Cornell University in the spring of 2012. We aimed to replicate and extend previous studies of complex onset coordination in Italian, French, and English, and to investigate coordinative patterns in Serbian and Hebrew, languages in which complex onsets have not been previously studied. The cross-linguistic coverage offered by previous studies is currently quite limited, hence our replications of prior studies and investigations of unstudied languages are a valuable contribution to the understanding of phonetic and phonological aspects of syllable structure.

The motivation for studying word-initial consonant sequences is derived from two sources. First, investigations of the syllable as a phonological domain have in recent years turned to articulatory differences between onset and coda consonants as a source of evidence for this domain (Browman & Goldstein, 1988; Krakow, 1989; Sproat & Fujimura, 1993; Byrd, 1995). Because the phonotactics of word-initial consonants are often similar to the phonotactics of syllable onsets, our study is relevant to understanding how articulatory patterns are associated with syllable structure. Second, available evidence indicates that two distinct coordinative patterns are available for word-initial consonant sequences, and in some cases (discussed below) this distinction correlates with phonological patterns involving syllabification. Hence cross-linguistic differences in articulatory timing of word-initial consonant sequences may be useful for understanding cross-linguistic differences in syllabification.

Our investigation and analysis of articulatory timing is guided by theoretical approaches to gestural coordination in the frameworks of Articulatory Phonology (Browman & Goldstein, 1988, 1990, 2000) and task-dynamics (Saltzman & Munhall, 1989). Articulatory phonology holds that in some languages, articulatory gestures associated with consonants in the onset of a syllable exhibit an in-phase timing relation to the following vowel. This C-V coordinative pattern contrasts with a theorized anti-phase C-C coordinative pattern. In a complex CC onset, both consonantal gestures are hypothesized to exhibit C-V coordination, but this competes with the anti-phase C-C timing relation. The result of these competing coordinative patterns is a compromise known as the c-center effect: relative to a singleton C, the timing of the prevocalic C gesture in a CC cluster is shifted closer to the following vowel, and the timing of the initial C gesture is shifter earlier relative to the vowel. Crucially, the midpoint (c-center) of these gestures maintains a stable relation to the vocalic gesture. This type of timing pattern in a word-initial cluster is henceforth referred to as *complex organization*. In contrast, in languages where word-initial consonants preceding the prevocalic C are not syllabified with the following V, these consonants are hypothesized not to exhibit C-V coordination. In that case, the timing of the rightmost C gestures should remain stable when preceded by one or more consonants. This type of pattern is referred to as *simplex coordination*. Articulatory studies have tested these predictions by comparing a variety of timing intervals in #CVC, #CCVC, and #CCCVC forms. Below we review these studies.

1.1 Previous studies

Investigations of coordination in word-initial consonants have interpreted results to indicate either simplex or complex organization. Languages in which timing patterns have been interpreted as simplex include Moroccan Arabic (Shaw et al., 2009), Slovak (Pouplier et al., 2011), Tashylhiyt Berber (Goldstein et al., 2007; Hermes et al., 2011), and Georgian (Goldstein et al., 2007). Languages in which timing patterns have been interpreted as complex include Italian (Hermes et al., 2008), English (Browman & Goldstein, 1988; Marin & Pouplier, 2010), and Continental French (Kühnert et al., 2006). There are a number of related studies investigating articulatory timing which do not examine word-initial consonant clusters specifically, but which bear upon the current investigation. For one, Byrd (1995) showed that in English, word-initial singleton onsets preceded by singleton or complex codas exhibit simplex timing with respect to the following vowel. Similar patterns have been reported in Krakow (1989, 1999) and Sproat & Fujimura (1993). These findings indicate that the word is a relevant domain in which to study articulatory timing. Table 1 summarizes previous studies of timing in word-initial consonant sequences specifically. Below we discuss a number of ways in which the methodological approaches of these studies differ, which makes it potentially difficult to draw firm conclusions by comparing them.

Language *Authors*	**N**	**Onset class.**	**Anchor landmark***	**Onset landmark***	**Context: clusters**
Moroccan Arabic *Shaw et al. (2009)*	1	simplex	V-off vC-extr	LE-trg, cc-midp, RE-rel	a___: {b, db, sb}, {t, kt},{l, gl} i___: {b, sb, ksb}, {d, kd, bkd}
Moroccan Arabic *Shaw et al. (2011)*	4	simplex	vC-extr	LE-trg, cc-midp, RE-rel	i___: {l, fl, kfl}, {b, sb, ksb}, {d, kd, bkd}
Slovak *Pouplier & Beňuš (2011)*	5	simplex	vC-mxspdons	LE-trg, cc-trg-rel, RE-rel	{l, vl, kl},{m, zm, sm}, {b, zb}, {r, br, kr}
Tashlhiyt Berber *Goldstein et al. (2007)*	1	simplex	V-trg	RE-trg	a __un: {m, sm, tsm}
Tashlhiyt Berber *Hermes et al. (2011)*	3	simplex	vC-trg	cc-trg, RE-trg	a ___: {f, kf, tkf},{k, lk, flk},
Georgian *Goldstein et al. (2007)*	2	complex/ simplex	V-trg	RE-trg	a___ial: {r, k'r, ts'k'r}
Italian *Hermes et al. (2008)*	2	complex/ s-simplex	V-extr	cc-extr, RE-extr	a ___: {l, pl, spl}, {r, pr, spr}, {p, sp},{f, sf},{v, sv}, {k, sk}
English *Browman & Goldstein (1988)*		complex	vC-acons (plosives)	LE-trg, cc-midp, RE-rel	V __Vts/dz: {p, pl, spl}
English *Honorof & Browman (1995)*	4	complex	vC-trg ([d])	RE-trg, LE-trg, cc-midp	cuff ___[eid]: {s, p, sp, l, pl, spl}
Continental French *Kühnert et al. (2006)*	2	complex	vC-acrel (burst)	cc-midp	Je vois __ et __: {n, fn, pn, kn}, {l, fl, pl, kl}
English *Marin & Pouplier (2010)*	7	complex	vC-extr	RE-extr, (cc-midp)	V(#)C(#)C___VC: {p, sp},{k, sk}, {m, sm}, {l, pl, kl}

*Landmark abbreviations are illustrated in Figures 1 and 2

Table 1. Summary of previous empirical studies testing for simplex/complex onset organization.

One major way in which the studies differ is with regard to the gestural landmarks that are used to define intervals. The assessment of simplex vs. complex timing involves a lag measure based on two gestural landmarks, which are points in time associated with an articulatory gesture. One of these is an anchor point (ANCH), which is associated either with the initial vowel of a word or the following consonant. The other is an onset consonant-related point which can either be a gestural landmark (see Figure 1) or c-center index (see Figure 2). Table 1 lists the types of anchors and onset points reported in each study.

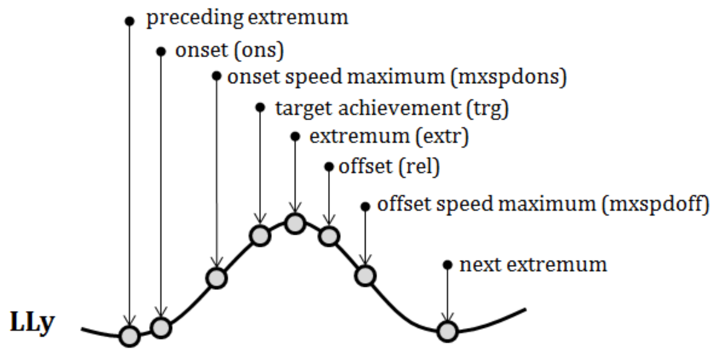


Figure 1. Schematic representation of gestural landmarks.

A variety of anchor points have been used across studies. These include the vocalic gesture target achievement (V-trg), extremum (V-extr), and offset (V-off), and the post-vocalic consonantal gesture peak speed (vC-mxpsdons), target (vC-trg), and extremum (vC-extr). Target achievement is typically defined as the point of time when a speed threshold relative to peak speed is surpassed, and 20% is a commonly used threshold (Gafos, Shaw, & Kirov, 2009). In the studies we reviewed, the choice or choices of some anchors over others is not always justified, but one important consideration is the post-vocalic consonant. If the articulation of this consonant does not provide a robust kinematic landmark and/or is inconsistent across a stimulus set, it is less suitable for an anchor point. Acoustic anchors have also been used for assessing onset timing. Browman & Goldstein (1988) used the acoustic onset of a post-vocalic plosive as an anchor point in their analysis of x-ray microbeam data. They argued that this point is representative of the target achievement of a post-vocalic consonant, i.e. vC-trg. Kühnert et al. (2006) used the acoustic release of the post-vocalic consonant as an anchor point. Given the wide range of variation in what anchors are used, it is reasonable to ask whether the choice of anchor makes a difference for the conclusions inferred from timing patterns. In analyses of timing in Tashyliyt Berber, the use of a post-vocalic anchor, vC-trg (Hermes et al., 2011) or a vowel-based anchor, V-trg (Goldstein et al., 2007) made no difference: both analyses found simplex timing of word-initial consonants. However, in Shaw et al. (2009) evidence for simplex vs. complex onset coordination in some sets of comparisons depended upon whether V-off or vC-trg was used as an anchor. In most other studies results are reported with only one anchor, so it is unknown whether different anchor points would affect the results.

For onset points a similar variety of landmarks have been used, and there are two approaches to assessing simplex vs. complex coordination. One approach involves measuring the lag between a gestural landmark associated with the rightmost consonant (RE) and a following anchor. The target (RE-trg), extremum (RE-extr), and release (RE-rel) of the consonantal articulation have been used in various studies. As discussed below, this approach constitutes *indirect evidence* for complex organization. An alternative approach involves the use of a c-center index, and provides *direct evidence* for complex organization. The c-center is a global landmark representing a point in time associated with a single consonant or cluster of consonants, which Browman & Goldstein (1988) hypothesized to be coordinated with the following vowel. If the timing of this index relative to the anchor is stable across forms of varying onset complexity, then complex timing is inferred.

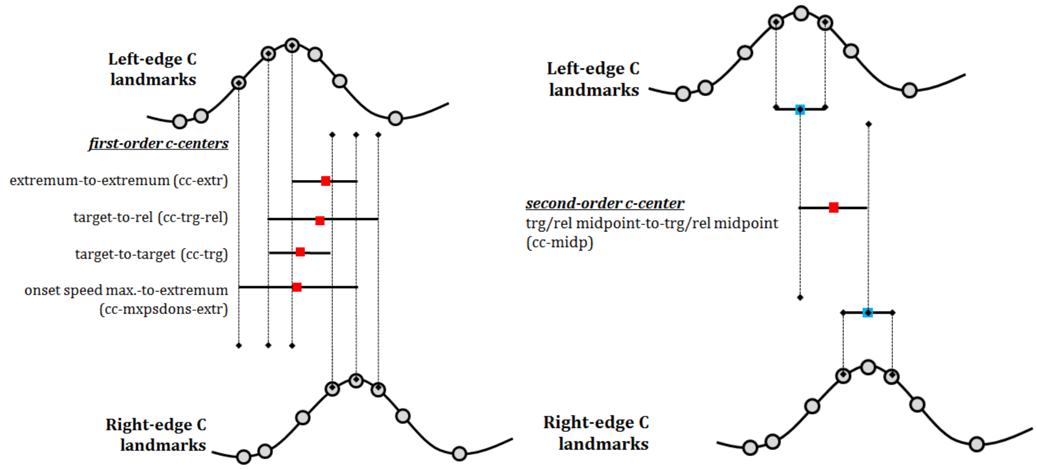


Figure 2. Different operational definitions of c-centers.

There are two types of c-centers that have been used in previous studies: *first-order* and *second-order c-centers*. Figure 2 illustrates various ways in which these c-centers can be defined, although not all of these have been employed in previous studies. In some cases, the c-center has been defined as the midpoint between landmarks associated with the leftmost and rightmost word-initial consonants preceding the vowel (i.e. LE and RE). This type of c-center is often used because plateaus associated with each articulatory gesture in a complex cluster cannot be reliably distinguished, which can be the case when the consonants are highly coarticulated due to sharing a common articulator (e.g. the common use of the tongue in /sl, spl/, cf. Honorof & Browman, 1995). We refer to these as "first-order" c-centers, because they are derived by averaging kinematic landmarks directly. In some studies, second-order c-centers are used, where a local c-center is calculated for each consonantal gesture as the midpoint between the target and release of that gesture, and subsequently the c-center is calculated as the midpoint of the leftmost and rightmost c-centers (cc-midp). We refer to these as "second-order" c-centers because they represent the midpoints of gestural plateau midpoints. As with anchor landmarks, variation in onset landmarks raises questions about drawing cross-linguistic comparisons from these studies. The decision to report one set of onset landmarks over another is sometimes not justified, but presumably there are reasons specific to the articulatory composition of the onsets being studied.

Many studies have reported lags using both a right-edge gestural landmark and a c-center; this is useful because it is possible that neither lags defined from the right-edge nor c-center may be particularly stable across a set of forms. However, some studies have reported only one of these measures. Logically speaking, if there are only two possible coordinative patterns (a consonant in a complex onset either is or is not coordinated with the following vowel), then within a comparison of {CVC, CCVC, CCCV} either a right-edge-C landmark should obtain a constant lag to a following anchor, or a c-center should do so. However, it is not unusual for neither an RE-landmark nor c-center to exhibit a relatively constant lag within a given comparison set. For example, in Hermes et al. (2008), the c-center lag increased significantly in {/r/, /pr/} for both speakers. Yet the extent of this increase was not as great as the extent of the decrease in the rightmost C, and hence the authors interpreted the pattern to indicate complex timing in /pr/. It is therefore useful to distinguish between indirect evidence (a non-constant RE-lag) and direct evidence (a constant c-center lag) for complex timing. A decrease in an RE-lag with more onset consonants present constitutes only indirect evidence for complex timing, since it does not necessarily imply that there exists a stably coordinated c-center. In contrast, a relatively constant c-center lag across forms of increasing onset size provides stronger, direct evidence for complex timing. There may be several reasons why neither an RE nor c-center index remains approximately constant across a comparison set. One reason could be that the onset and/or anchor points analyzed do not represent events that are coordinated by the production system; currently there is no consensus on which indices are the most appropriate ones. Another reason could be that there are subtle effects of coarticulation or methodological factors that give rise to deviation from the predictions of the theory.

Even when the same onset and anchor points are used, there is no standard approach taken to assessing simplex vs. complex timing. Some studies have performed ANOVAs on one or more types of lags, the idea being that a non-significant effect of the factor CLUSTER TYPE (i.e. CC vs. C) indicates stability. When this analysis is conducted by collapsing across different types of segments, the results may be misleading, especially if a SEGMENT × CLUSTER TYPE interaction is present. A more detailed approach is to perform pairwise comparisons on lags for groups of word-initial consonant sequences sharing the same right-edge C, e.g. the group {r, pr, spr} from Hermes et al. (2008). An alternative approach to assessing timing involves comparison of the standard deviations or relativized standard deviations (RSD, i.e. standard deviation as a percentage of mean) of different types of lags computed across tokens from a group. For example, one form of analysis reported in Shaw et al. (2009) compared the RSDs of c-center lags vs. RE-rel lags for various groups and found that the RE-lag RSDs were lower, suggesting that the rightmost consonant is more stably-timed to the following vowel than the c-center. One issue with variance-based approaches as implemented in the reviewed studies is that statistical tests for differences in lag variances are not conducted: whether a difference in variance between two lag measures is significant is unclear. Moreover, even if a given lag measure is found to be least variable across cluster types, this does not imply that CLUSTER-TYPE has no significant effect on the mean lag. Hence analyses based on lag variances alone can provide only indirect evidence for complex timing.

A complication that arises in generalizing findings is that segment-specific and speaker-specific variation appear to be important. For example, in a study of Georgian, Goldstein et al. (2007) report a decrease in RE-lag with increasing onset complexity for one subject, but no such decrease for another, suggesting complex organization in the former and simplex organization in the latter. Whether this difference is dialectal or idiolectal is unknown. Specific types of clusters may also pattern differently within a given language. In Italian, Hermes et al. (2008) report evidence for complex timing of clusters except for /sC/ and /sCC/ clusters, where the addition of the /s/ does not result in a rightward shift of the rightmost consonant.

Some types of segments may present special challenges to analyses of onset coordination. For example, liquids such as /l/ and /r/ may be articulated quite differently as singleton onsets compared to their articulation as members of a complex onset. It is noteworthy that there are only a couple studies which provide direct evidence for complex organization of these segments, and even in those, the results are not entirely unambiguous. To wit, Marin & Pouplier (2010) report only indirect evidence for complex timing of /Cl/ (based on RE-lags alone); Browman & Goldstein (1988) reported indirect (variance-based) evidence for {l, pl, spl}. Hermes et al. (2008) reported direct evidence, but patterns conflicted depending upon the following vowel. Only in Kühnert et al. (2006) is direct evidence presented for complex organization of /Cl/. The special challenges related to analysis of timing involving liquids are also evident in variation in the articulatory movements that are analyzed to obtain landmarks. Many segments are analyzed in the same way across studies. For example, with few exceptions, bilabial consonant landmarks are identified with lip aperture (the degree of opening between the lips); labiodental fricative (/v/ and /f/) landmarks with lower lip vertical position; coronal stop, nasal, and fricative landmarks with the position of the tongue tip; and velar stops with position of the tongue body. In contrast, there is a greater amount of variation in how liquid landmarks have been identified: Kühnert et al. (2006) used tangential velocity of the tongue tip; Pouplier & Beňuš (2011) used the retraction of the tongue dorsum to represent /l/ and /r/ articulation; most others have used the vertical position of the tongue tip. Laterals are additionally challenging because their constrictions are asymmetric, and electromagnetic articulometry studies typically locate lingual sensors in the mid-sagittal plane; hence the maximally displaced portion of tongue in /l/ is typically not measured. Furthermore, since liquids may coarticulate strongly with other lingual consonants and may vary substantially across languages, there may be no general best approach.

Finally, it should be noted that the number of speakers in most studies is quite small. Table 1 shows that sample sizes of 1-3 speakers per language are typical. This is not surprising given the difficulty of collecting and analyzing articulatory data, and of course, the present study is no exception. One related issue involves how articulatory data are typically measured. In electromagnetic and x-ray articulometry, some number of points on the tongue are tracked. Although attempts are made within studies to standardize where on the tongue sensors are placed, gender- and individual-related variation in vocal tract geometry across speakers, along with constraints on the number of sensors that can be used, make it impractical to locate sensors exactly where constrictions are formed for all lingual consonants. Moreover, it is not always possible to place sensors far back enough on the tongue to fully capture the movements of the tongue body associated with low or back vowels, in which case the most posterior sensor is taken as a rough proxy for this movement. In conjunction with typically small sample sizes, these facts warrant caution in drawing conclusions that would generalize from the behaviors of a couple of speakers to a population.

1.2 The relation between articulatory organization and phonology

An obvious question to ask concerns possible correlations between the phonological status of prevocalic consonants and their gestural organization. In other words, can we detect any phonological consequences of the articulatory organization of prevocalic consonants, or any articulatory consequences of their phonological organization? It is known that languages can differ with regard to how word-initial consonants are parsed into syllables. In some languages, notably in English, the word-initial consonants in a string such as CCV are grouped in a single syllable [CCV], that is, both prevocalic consonants are integrated into the onset. In other languages, such as Moroccan Arabic and Tashylhiyt Berber, a word initial CCV sequence is phonologically parsed as [C.CV]; that is, only the immediately prevocalic consonant is syllabified with the following vowel. It is of interest that this phonological distinction correlates with differences in the articulatory timing of the prevocalic consonants. As already noted, according to the articulatory studies of English, the articulatory gestures associated with each consonant in word initial CCV sequences have been shown to exhibit a similar coordinative relation to the vowel, which corresponds to complex gestural organization. By contrast, articulatory studies of Moroccan Arabic (Shaw et al. 2009) and Tashylhiyt Berber (Goldstein et al., 2007; Hermes et al., 2011) report simplex gestural organization of word-initial prevocalic consonantal sequences, with only the rightmost consonant coordinated with the following vowel. These findings suggest that complex gestural organization is associated with consonantal sequences that are phonologically parsed into syllable onsets. It is further possible that, within a given language, certain types of prevocalic consonant sequences exhibit complex, while others exhibit simplex, gestural organization. This pattern has been reported for Italian. According to Hermes et al. (2008), prevocalic CC sequences exhibit complex gestural organization, with the exception of sC clusters, which exhibit simplex organization. Phonologically, this difference correlates with the syllabic status: while prevocalic CC sequences generally form an onset, in /s/-initial sequences only the pre-vocalic consonant syllabifies as an onset, while /s/ preferably occupies the coda position. Finally, a broader issue is whether prevocalic consonant sequences that phonologically correspond to onsets could exhibit simplex organization. It could be that, in languages with large inventories of onset clusters, the less marked groupings, typically consisting of obstruent/sonorant sequences (cf. Clements 1990), have complex gestural organization, while the more marked groupings have simplex organization. Also, in languages undergoing a phonological change from simple to complex onsets, simplex gestural organization may prevail in the initial stages of the change. In sum, we cannot exclude the possibility that, in some cases, phonological onsets may exhibit simplex organization. Whether this is indeed the case is an empirical question.

1.3 Hypotheses

In general, our hypotheses are derived from patterns observed in previous studies, or where no such studies have been conducted, from our expectations based upon phonological patterning of word-initial consonant sequences. Language-specific hypotheses are presented in sections 3-7 in combination with background, methodological details, and results for each language. For example, in English and French, we hypothesize complex timing (i.e. c-center coordination) because that is consistent with previous studies of Continental French (e.g. Kühnert et al., 2006). In languages in which simplex timing has been reported, there is sometimes phonological evidence that suggests that word-initial, non-prevocalic consonants are not organized with the following vowel. This is the case for Tashylhiyt Berber and Italian /s/, as described above. Hence if there is any phonological evidence that bears upon hypothesizing simplex timing, this serves as our rationale for hypotheses. Otherwise, we hypothesize complex timing, under the presumption that this is the typical pattern when all word-initial consonants are syllabified with the following vowel. For some languages, we included word-initial clusters which are non-occurring in the language. For these cases, our predictions are based on our intuitions regarding the similarity of the non-occurring clusters and clusters that do occur in the language to formulate hypotheses. The generic predictions that derive from hypotheses of simplex and complex timing are as follows:

Simplex timing predictions: the mean lag of the prevocalic consonantal gestural landmark (RE-lag) will not differ in C vs. CC, or in CC vs. CCC tokens. Correspondingly, the c-center lag will increase when more word-initial consonants are present.

Complex timing predictions:
(a) <u>Indirect evidence for c-center coordination:</u> the mean lag of the prevocalic consonantal gestural landmark will decrease in CC vs. C, and in CCC vs. CC.
(b) <u>Direct evidence for c-center coordination:</u> the mean lag of the c-center will be constant across C, CC, and CCC tokens.

2 Method

2.1 Participants and stimuli

Word-initial complex onsets were elicited in Italian, Montreal French, Serbian, English, and Hebrew. For each language, one native speaker was recruited and he or she participated in a one-hour recording session. Word lists were designed for each language to enable comparison of a variety of simplex and complex onsets in the language. For English, Serbian, and Hebrew, we aimed to test onsets in a phonetic context that was as controlled as possible, and hence most of the words used were nonwords in those languages. To control the phonetic context, identical vowels and postvocalic consonants were used for all stimuli. For Italian and Montreal French, we aimed to replicate and extend previous studies, and hence the word lists were designed to be consistent with those studies; in these cases, the word lists consisted of mostly real words, and for some onsets, pseudowords. However, when possible we preferred real words at the expense of absolute control over phonetic context. The combinations of onsets for each language and other stimuli details are discussed in the language-specific sections below. Word lists are presented in an Appendix. In all cases, the words were elicited in the context of a carrier phrase which ended with a low vowel, which facilitates detection of onset landmarks in word-initial consonantal gestures. The languages and carrier phrases are listed in the table below:

language	carrier phrase	gloss
Italian	Per favore dica ____ di nuovo.	Please say ____ again.
Serbian	Pa ta ____ je smešna.	But that ____ is funny.
Montreal French	Tu diras ____ à Normand.	You said ____ to Norman.
Hebrew	Haish kana ____ hayom.	The man bought ____ today.
English	He saw ____ yesterday.	

Table 2. Carrier phrases for each language.

language	onset groups					
	{sf, f, z}r	{f, z}l	{s}f	{p}s	{s}p	{s, z}k
Italian	{sp, zb, p}r	{zb, p}l	{z}v		{z}b	
	{sk, zg, k}r	{sk, k}l				
	{s, f}r	{f, s}l	{s, k}f	{p, k}s		{p, s}k
Serbian	{sp, p}r	{sp, p}l				
	{sk, k}r	{sk, k}l				
	{sm, m}r	{sm, m}l				
Montreal French		{f, s}l	{s}f	{p}s	{s}p	
		{p}l				
		{k}l				
	{s, x}r	{s, x}l		{p, k, x}s	{s, t, k}p	{p, s, t}k
Hebrew	{sp, p}r	{sp, p}l				
	{sk, k}r	{sk, k}l				
	{s, f}r	{s, f}l	{p, s, k}f		{s, k}p	{p, s}k
English	{sp, p}r	{sp, p}l				
	{sk, k}r	{sk, k}l				

Table 3. Complex-simplex comparisons tested for each language.

2.2 Procedure

Prior to each recording session, speakers read the word list out loud in order to familiarize themselves with the target words and in order for us to check whether their pronunciations matched our expectations. Speakers were informed beforehand if any or all of the words were nonwords, and were told to produce the nonwords as they would expect to do if they were real words. They were then familiarized with the carrier phrase, and were told that on each trial a word would appear on the screen, to which they should respond by saying the carrier phrase with that word in the appropriate place. During the experiment, speakers were seated facing a monitor on which the target words were presented in the standard orthography of their language. The words remained on the screen for 5 s, and there were two 2 s between each trial. Trials were grouped into blocks within which all target words were presented in random order. After each block, speakers took a 45-60 s break and then performed another block. Our word lists varied in length across languages from 28-36 words. This allowed for 12-14 blocks to be recorded during each session, and hence for 12-14 tokens of each target word form to be collected.

Acoustic recordings were made with a shotgun microphone positioned approximately 2.5 feet from the speaker. Articulatory recordings were made with an NDI WAVE articulometer sampling at 100 Hz. The WAVE articulometer consists of a magnetic field generator contained in a box whose position is adjustable with jointed metal bars. The field generator was always positioned on the right side of the heads of our subjects, such that its horizontal coordinate corresponded to the anterior-posterior direction, its vertical coordinate to the inferior-posterior direction, and its axial coordinate to the left-right direction. Sensors were adhered to reference positions and moving articulators using a dental adhesive. Reference sensors were placed on the nasion and the right and left mastoid processes. In our default sensor location protocol, articulator sensors were placed in the mid-sagittal plane on the lower lip (LL), upper lip (UL), the jaw as represented by the gumline beneath the lower front incisors (JAW), the tongue tip (TT), i.e. approximately 2 cm posterior to the physical apex of the tongue, and the tongue dorsum (TD), approximately 4-5 cm posterior to the TT sensor. However, we sometimes were forced to deviate from this protocol. Our placement of the TD sensor was influenced by how far out subjects were able to protrude their tongues, so in some circumstances this sensor was more anterior than our target. Difficulties in attaining sensor adherence to the lower incisors or gumline in one case led us to adhere the JAW sensor to the skin over the left-front side of the mandible. Speaker-specific deviations from the default protocol are detailed in the language-specific sections below.

Prior to data collection, a biteplate was used to measure the orientation of the occipital plane relative to the reference sensors. The biteplate consisted of a thin but rigid plastic plate with three sensors arranged in a triangle. A brief recording was made while the subject bit down gently on the plate. This allows for computation of a “basis” position for the reference sensors such that the biteplate is parallel to the horizontal and axial coordinates of the field generator, which is made approximately parallel to the ground by using a level. The reference basis is also translated so that the most anterior biteplate sensor is at the origin of the coordinate system. In processing the experimental data, the sensor data were lowpass-filtered (4^{th} order Butterworth, 5 Hz for reference sensors, 10 Hz for articulator sensors). Then for each time sample the sensors were rotated and translated so that the reference sensors aligned with the basis. In effect, this corrects for head movement within subjects and standardizes the data across subjects by enforcing a coordinate system whose axes are parallel/perpendicular to the occipital plane.

2.3 Data analysis

For each trial, time-aligned acoustic and articulatory data are used to extract relevant acoustic and kinematic landmarks. Fig. 3 shows an example of the data from a single trial, in this example the form /splata/ from a Serbian speaker. The vowel from the carrier phrase preceding the target word and the vowel following the consonant cluster are indicated with vertical lines in the waveform. The first step in extracting landmarks is to identify these vocalic reference points. This is accomplished by using a low-pass filter of the acoustic waveform to identify peaks in acoustic energy associated with vowels in the carrier phrase and target word. For some forms it was necessary to locate the vowels by hand. The kinematic landmarking was accomplished by first identifying position or velocity extrema in the relevant sensor position data, and subsequently locating preceding extrema, following extrema and other landmarks illustrated in Figure 1. A 20% speed threshold was used for locating onsets, targets, and releases. To ensure identification of the correct landmark, a cost function was defined which penalized distance of the initially identified extremum from a reference point. The reference points were defined as the midpoints of sub-intervals determined by partitioning the interval between the preceding frame vowel and initial vowel of the target word, such that there were as many sub-intervals as consonants.

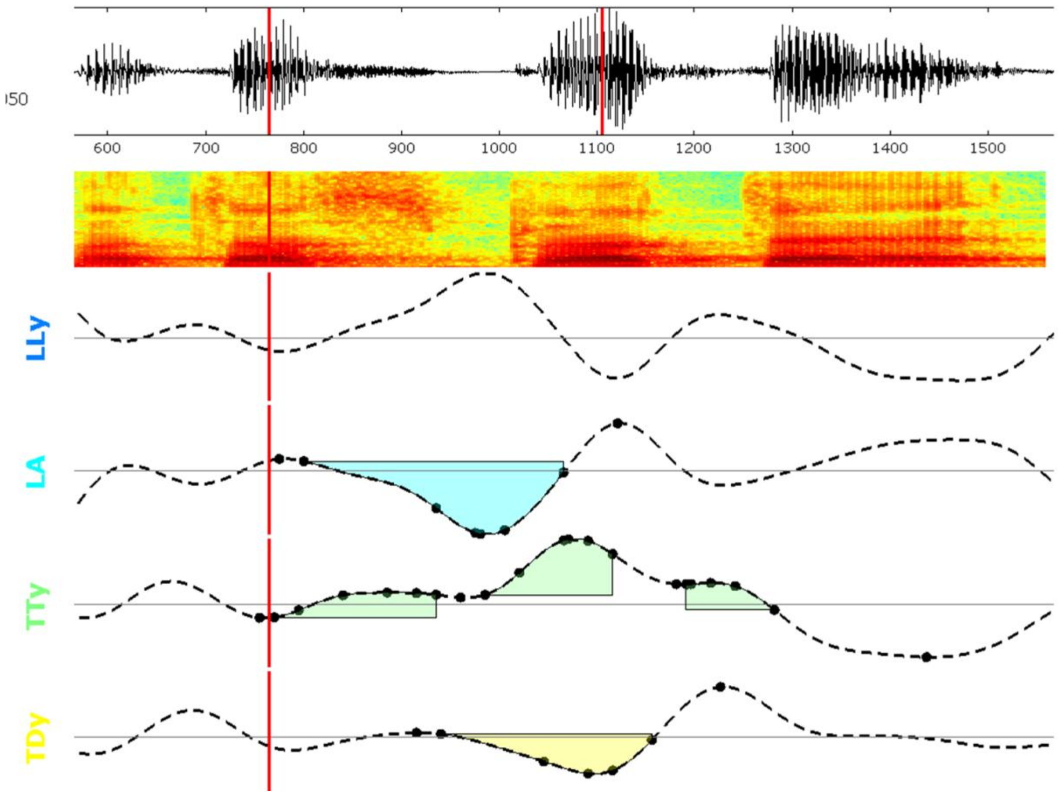


Figure 3. Example of acoustic and kinematic data with landmarks. From Serbian /splata/.

All landmarks were subsequently inspected and corrected when necessary. In some clusters separate plateaus are not evident in the movement data; these occurrences are reported in the language-specific sections and only first-order c-centers can be obtained from them. The articulator data used for landmarking depended upon the place of segmental articulation. For bilabial stops and nasals, we used the tract variable lip aperture (LA), defined as the Euclidean distance between the LL and UL sensors. For labial fricatives /f/ and /v/, we used the vertical position of the LL. For coronal stops, fricatives, and nasals, the vertical position of the TT was used, and for dorsal stops, the vertical position of the TD was used. For vowels, it was necessary to use a wider variety of articulator data. TD was used for the low vowel /a/, but alternatives were employed for high vowels in the Montreal French and Italian stimuli. Likewise, language-specific approaches to landmarking /l/ and /r/ were employed; these were the most challenging articulations to landmark, due to coarticulation with lingual consonants. Approaches for liquids and vowels are detailed in the language-specific methods.

Analyses were conducted on a language-by-language basis, with efforts to be consistent across languages. After landmarks were extracted for all tokens in a given language, all of the RE-lags and c-center lags illustrated in Figures 1 and 2 were calculated, although most were not analyzed. Across experiments we obtained measurements from 10-14 tokens for each cluster, depending upon the length of the word list used and occurrence of errorful responses. Outliers for each lag were excluded on a cluster-by-cluster basis, using a ±2.0 z-score criterion. Subsequently the mean lag and standard error were calculated for each cluster. Figures shown in the language-specific results (sections 3-7) illustrate these mean lags along with ±2.0 standard error bars. Each figure presents RE-lag and c-center lags for a group of clusters related by sharing the same RE consonant. Due to the preliminary nature of this report, we focus on the qualitative patterns and do not present pairwise comparisons or statistical tests; however, we note that non-overlap of ±2.0 standard error intervals between two samples is expected to be significant in a *t*-test.

3 Results: Italian

Our study of Italian attempts to replicate and extend previous research by examining onset clusters in Italian. Hermes et al. (2008) reported direct evidence for a complex timing in onset clusters, with the exception of /s/-initial clusters. Mean c-center lags did not differ across {p, pl, pr}, but the addition of an /s/ to these onsets resulted in an increase in c-center lag and a decrease in RE-lag. This suggests that unlike other consonants, /s/ is not syllabified with a following vowel. Hermes et al. (2008) did not test sonorant C in an /sC/ context, and so our study incorporates /sl/ [zl] and /sr/ [zr] clusters to address whether word-initial /s/-sonorant clusters exhibit a simplex timing pattern.

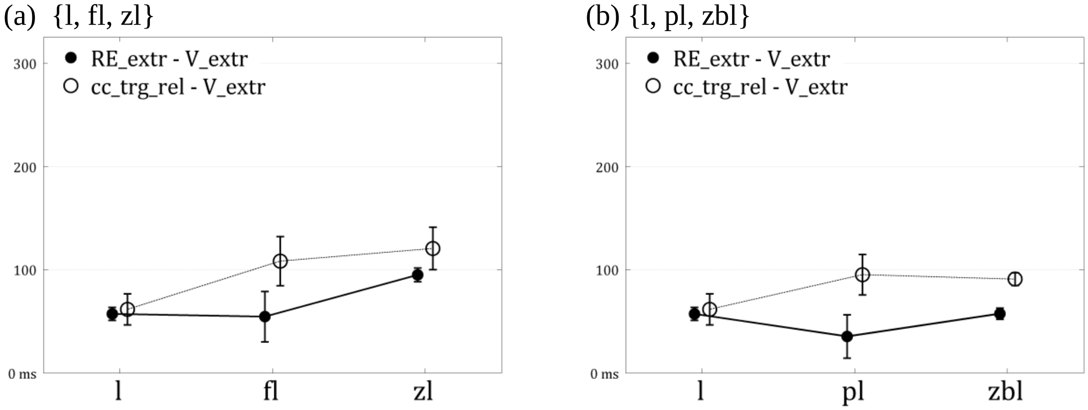
The Hermes et al. (2008) results are striking because the exceptional timing behavior of /s/ appears to relate to its phonological status: as the first element of a cluster, /s/ acts as a coda consonant rather than an onset. This is supported by three types of evidence: closed syllable shortening, *raddoppiamento sintattico*, and morphological alternations. The first phenomenon is demonstrated in phonetic studies (Farnetani and Kori 1983, Vogel 1982), in which stressed vowels are shortened before word-internal /sC/ clusters. Raddoppiamento sintattico (RS) provides evidence from the interaction of syntax and prosody that /sC/ clusters are heterosyllabic rather than tautosyllabic: in tautosyllabic onset clusters, the first member of the cluster geminates across a word boundary when it is both preceded and followed by a stressed vowel, as in *citta` triste* [tʃitːa tːriste] 'sad city' (McCrary 2002, Vogel 1982, Chierchia 1986). When this occurs, the first timing unit of the geminate associates leftward into coda position, e.g. [tʃit.ta**t.t**ris.te]. Where the first member of this cluster is an /s/, however, *raddoppiamento* does not occur: *citta` sporca* 'dirty city' is realized as [tʃit:a sporka], e.g. [tʃit.ta**s.p**or.ka]. The final piece of evidence for the heterosyllabic status of /sC/ clusters comes from the allomorphy of definite and indefinite articles preceding word-initial /sC/: whereas onset clusters in masculine nouns are preceded by the indefinite article [un] and the definite article [il], as in *un proiettore* 'a projector', *il platino* 'platinum (def.)', /s/-initial clusters take [uno] and [lo], respectively, as in *uno schermo* [uno skermo] 'a screen', *lo strato* 'layer (def.)' (Davis 2009, Morelli 1999). In these cases, /s/ is argued to syllabify as a coda for the preceding [o] nucleus. With respect to the morpho-phonology and phonological evidence for syllabification, [z] behaves identically to /s/: *uno sbalzo* [uno zbaltso] 'a jolt', *lo sdraio* [lo zdrajo] 'lawn chair (def.)'.

Based on Hermes et al. (2008), we expected to observe direct and indirect evidence of complex timing in onsets (excepting sibilant initial ones), i.e. no change in c-center and a decrease in RE-lag. We furthermore expected to observe no change in RE-lag and a corresponding increase in c-center lag for the sibilant-initial onsets, i.e. for sCC vs. CC clusters and sC vs. C clusters. Our word list (Appendix, Table A1) conforms to the phonological restrictions of Italian. Two-member consonant clusters may consist of an obstruent followed by a liquid (/pl, gl, zr, kl/), or a sibilant followed by an obstruent, including nasals (/st, sp, zg, zm/). Sibilants [s, z] must agree in voicing with the following consonant: /zr, zb, zm/ and /st, sp, sk/ are licit, but /*zp, *sr, *sn/ are not. Clusters may consist of maximally three consonants, but in this case the first member must be a sibilant [s, z], the second must be a non-sibilant, non-nasal obstruent, and the third must be a liquid [r, l]. All target words had initial stress. Most stimuli were existing lexical items, although a few were phonologically-licit nonce words. Wherever possible, the vowel following the onset cluster was restricted to /i/ or /e/ for consistency with Hermes et al. (2008), and was followed by a non-geminate consonant. In some cases, gaps in the Italian lexicon required the use of words that do not conform precisely to these phonological restrictions. Because the post-vocalic consonants of our stimuli were not controlled due to our preference for lexical stimuli, we used for the anchor point the vertical maxima of the TD sensor for the vowels /i/ and /e/, and the minima for the vowels /a/ and /o/. For /l/ and /r/ the RE-lag was calculated using vertical position of the TT sensor (the extremum for /l/, the target for /r/).

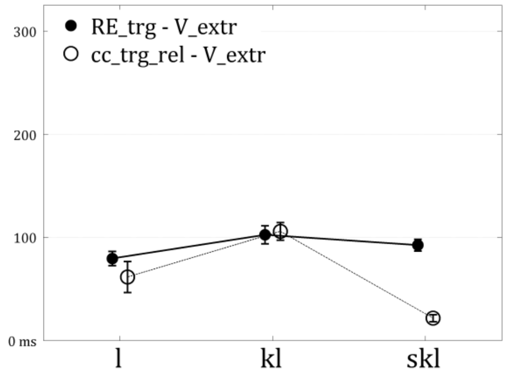
Evidence for complex timing was generally mixed. For {l, fl}, {l, pl}, and {l, kl} comparisons, cc-lags increased for complex clusters, and RE-lags remained approximately the same (Fig. 4a-c). The same was true for {r, fr} and {r, kr} (Fig. 4d,f)—neither of these patterns are indicative of complex organization. Only in {r, pr} did we observe the predicted pattern: RE-lag decreased about 30 ms, and cc-lag exhibited a more modest increase of about 15 ms (Fig. 4e). For {s, ps} we observed indirect evidence in the form of an approximately 50 ms decrease in RE-lag, but this was contradicted by a similar increase in cc-lag (Fig. 4i). Note that the unpredicted increases in cc-lag are consistent with the data in Hermes et al. (2008): the indirect evidence (decrease in RE-lag) is contradicted by an increase in cc-lag, yet the latter is of lower magnitude.

Evidence for simplex timing in sibilant-initial clusters was also mixed, but generally more prevalent. For {pr, spr}, the RE-lag remained the same, while the cc-lag increased by 40 ms (Fig. 4e). For {pr, zbr}, the RE-lag increased a modest 20 ms, while the cc-lag increased by 60 ms. Likewise, for {r, zr} (Fig. 4d) and {v, zv} (Fig. 4g), the RE-lag remained about the same and the cc-lag increased. These patterns support the hypothesis that /s/ exhibits simplex timing in word-initial clusters. Other relevant comparisons exhibit more ambiguous evidence for simplex timing of /s/. For {l, zl} both RE-lag and cc-lag increased, although the latter was of greater magnitude (Fig. 4a). For {f, sf} (Fig. 4g) the cc-lag decreased a modest 20 ms and RE-lag increased about the same amount. In several cases, evidence for simplex timing is contradictory: {pl, zbl} (Fig. 4b) and {fr, sfr} (Fig. 4d) exhibited constant RE-lags, but also did not differ in cc-lag; note, however, that the vowel differed between {pl, zbl} and hence the comparison is not well-controlled. {kl, skl} exhibited constant RE-lag, but also a large decrease in cc-lag (Fig. 4c). In comparing {kr, skr, sgr} (Fig. 4f), RE-lag decreased in the s-initial clusters while cc-lag remained the same—this would actually indicate complex timing. {p, sp} remained fairly stable in both RE- and cc-lags. {p, zb} exhibited decreases in both RE- and cc-lags, but this may be attributable to a difference in the following vowel between these stimuli.

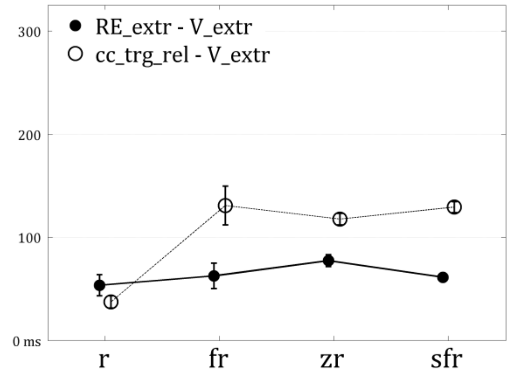
(a) {l, fl, zl} (b) {l, pl, zbl}



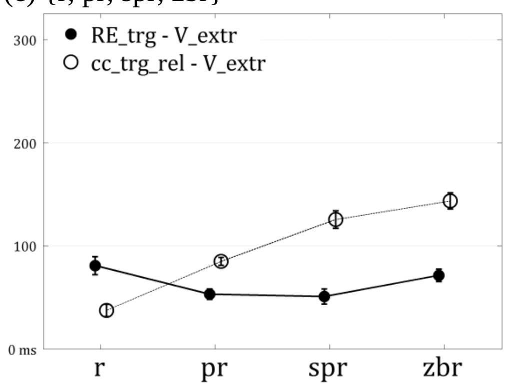
(c) {l, kl, skl}



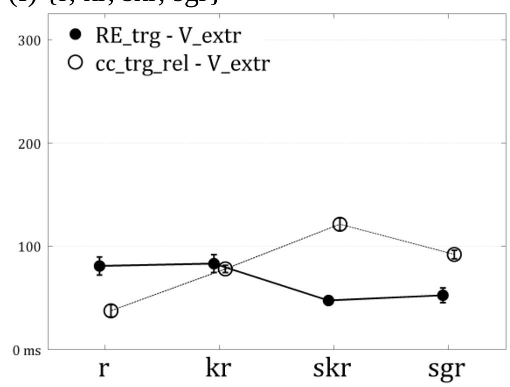
(d) {r, fr, zr, sfr}



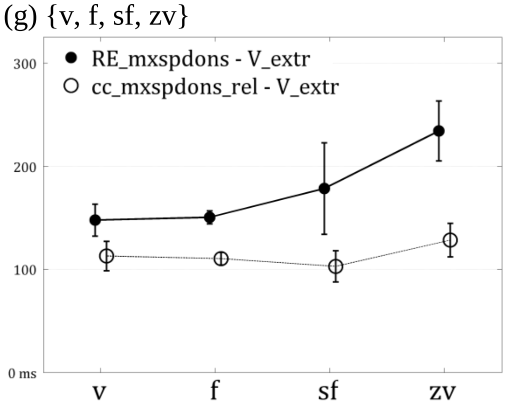
(e) {r, pr, spr, zbr}



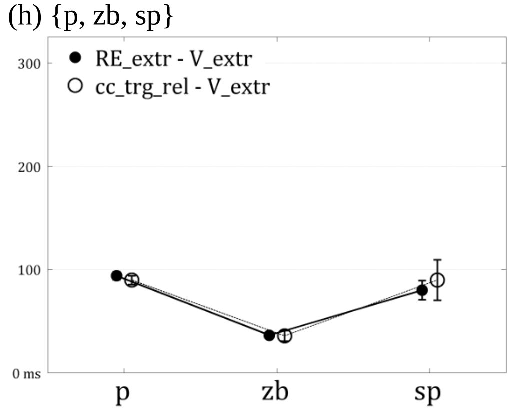
(f) {r, kr, skr, sgr}



(g) {v, f, sf, zv}



(h) {p, zb, sp}



(i) {s, ps}

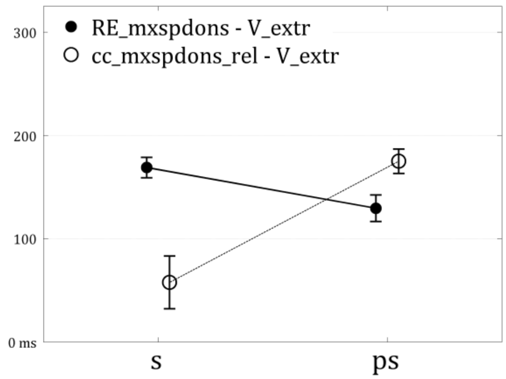


Figure 4. Right-edge and c-center lags for Italian word-initial clusters.

There are several issues that suggest caution in interpreting our results here. First, we observed that the use of a post-vocalic /i/ or /e/ made analysis of gestural landmarks associated with coronal liquids /r, l/ less robust. The high position of the tongue body for these vowels leads to greater variance in extraction of the relevant kinematic landmarks. Second, the coronal liquid gestures exhibit characteristics that can make articulatory tracking less reliable: /l/ involves an asymmetric constriction, so it is possible that our mid-sagittal located TT sensor does not represent the location of the tongue that is maximally displaced; /r/ may be articulated with minimal TT displacement, instead involving retraction of the tongue body or bunching of the tongue—these may be more likely in clusters, as well. Hence it is not clear that our method was well-suited to identifying landmarks associated with /r/ and /l/.

4 Results: Montreal French

Our study of French attempts to extend prior research to a previously unexamined dialect, Montreal French. Kühnert et al. (2006) reported direct evidence for a complex timing in {f, p, k}/n/ and {f, p, k}/l/ onset clusters in Continental French. They used the acoustic release of the post-vocalic consonant as an anchor point and analyzed the c-center lag (second order). They found no significant differences in c-center lag across these clusters. Our study also included several obstruent-obstruent clusters, which were not examined by Kühnert et al. (2006). These clusters have a low lexical frequency and in some cases violate the sonority sequencing principle (Clements 1990), hence they may differ from obstruent-sonorant clusters.

Based on the previous findings and a presumption of similarity between Montreal French and Continental French, we expected to observe direct evidence of complex timing in C-sonorant clusters. For obstruent-obstruent clusters, we hypothesized simplex timing. Our word list (Appendix, Table A2) conforms to the phonological restrictions of Montreal French. We examined {p, f, s, k}/l/ clusters, and several obstruent-obstruent clusters: /ps, pt, st/. The /ps/ and /pt/ clusters are derived from loanwords and do not occur frequently in the Montreal French lexicon. We used solely lexical stimuli, and thus we were not able to fully control the vowel or the post-vocalic consonant. When possible, we selected stimuli with the vowel /a/, but for several items other vowels were necessary. For /a/, /e/, and /o/, the vertical minimum of the JAW was the most robust vocalic anchor landmark so we used that one; for /i/, the vertical maximum of the TT was used.

In no comparisons did we observe any evidence for complex timing; instead, our results are generally consistent with simplex timing. For {l, fl, sl}, RE-lags were about the same, while cc-lags increased about 50 ms in complex clusters (Fig. 5a). Similarly, for {l, pl} (Fig. 5b), RE-lag remained constant, while cc-lag increased by about 30 ms. For {l, kl} (Fig. 5b), RE-lag increased by around 10 ms, and cc-lag increased by approximately 45 ms. In contrast to Kühnert et al. (2006), these patterns are suggestive of simplex timing. Similarly, for the obstruent-obstruent clusters {f, sf} (Fig. 5c), {p, sp} (Fig. 5e), and {t, pt} (Fig. 5f), RE-lag remained constant and cc-lag increased substantially—this again suggests simplex timing for these clusters. However, for the {t, pt} and {f, sf} stimuli comparisons, the following vowel is different and this may influence the location of the anchor point. The same confound is present for {s, ps} (Fig. 5d), where we observed a similar increase in both RE- and cc-lags.

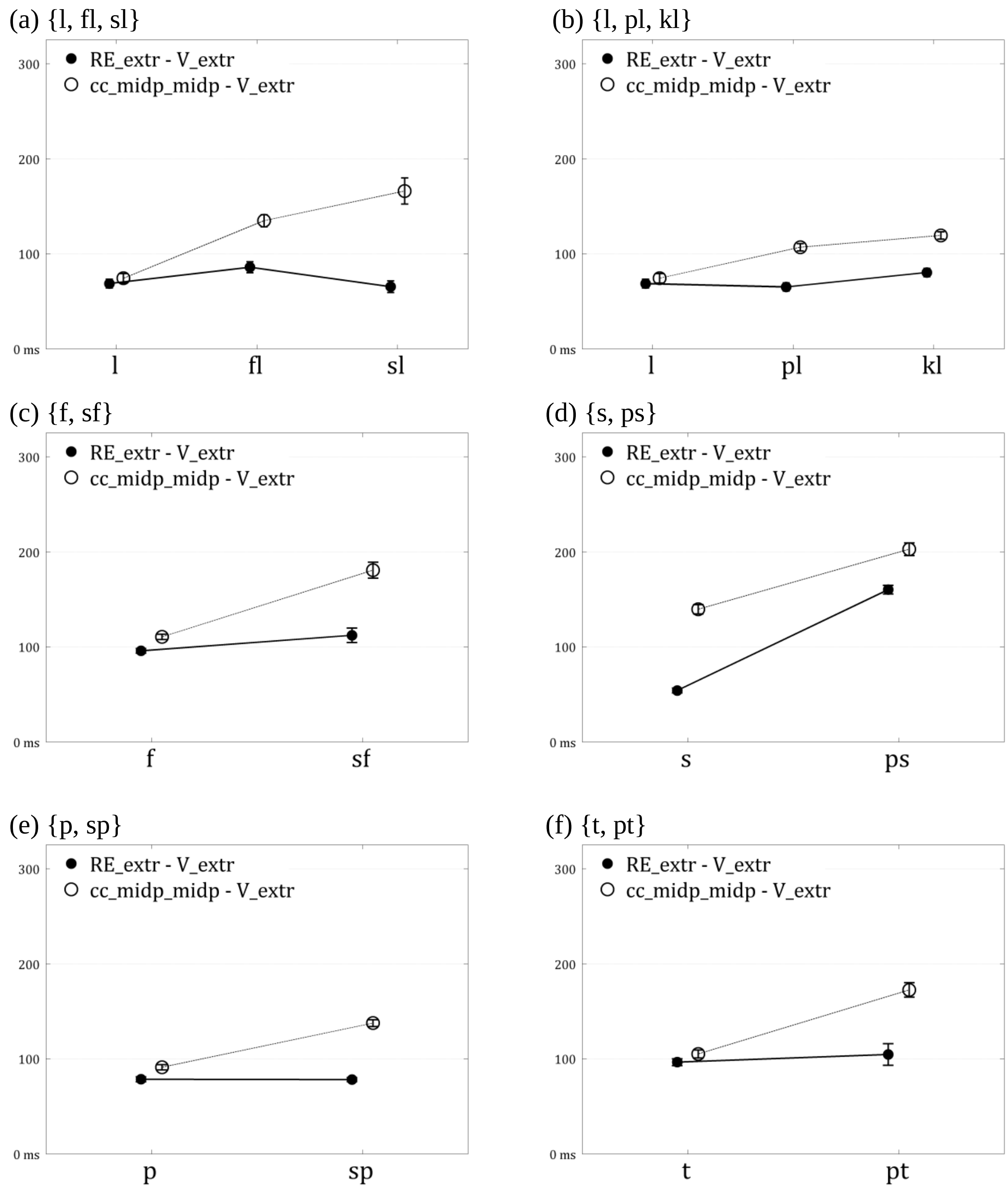


Figure 5. Right-edge and c-center lags for Montreal French word-initial clusters.

In sum, our results diverge markedly from those of Kühnert et al. (2006). Based on our data, Montreal French exhibits simplex timing in word-initial clusters. However, we examined only C/l/ clusters, not C/n/ clusters, so it is possible that the latter pattern differently. In examining several obstruent-obstruent clusters, we also observed evidence for simplex timing, although only one of the comparisons {p, sp} was free of a potential confounding difference between vowels.

5 Results: English

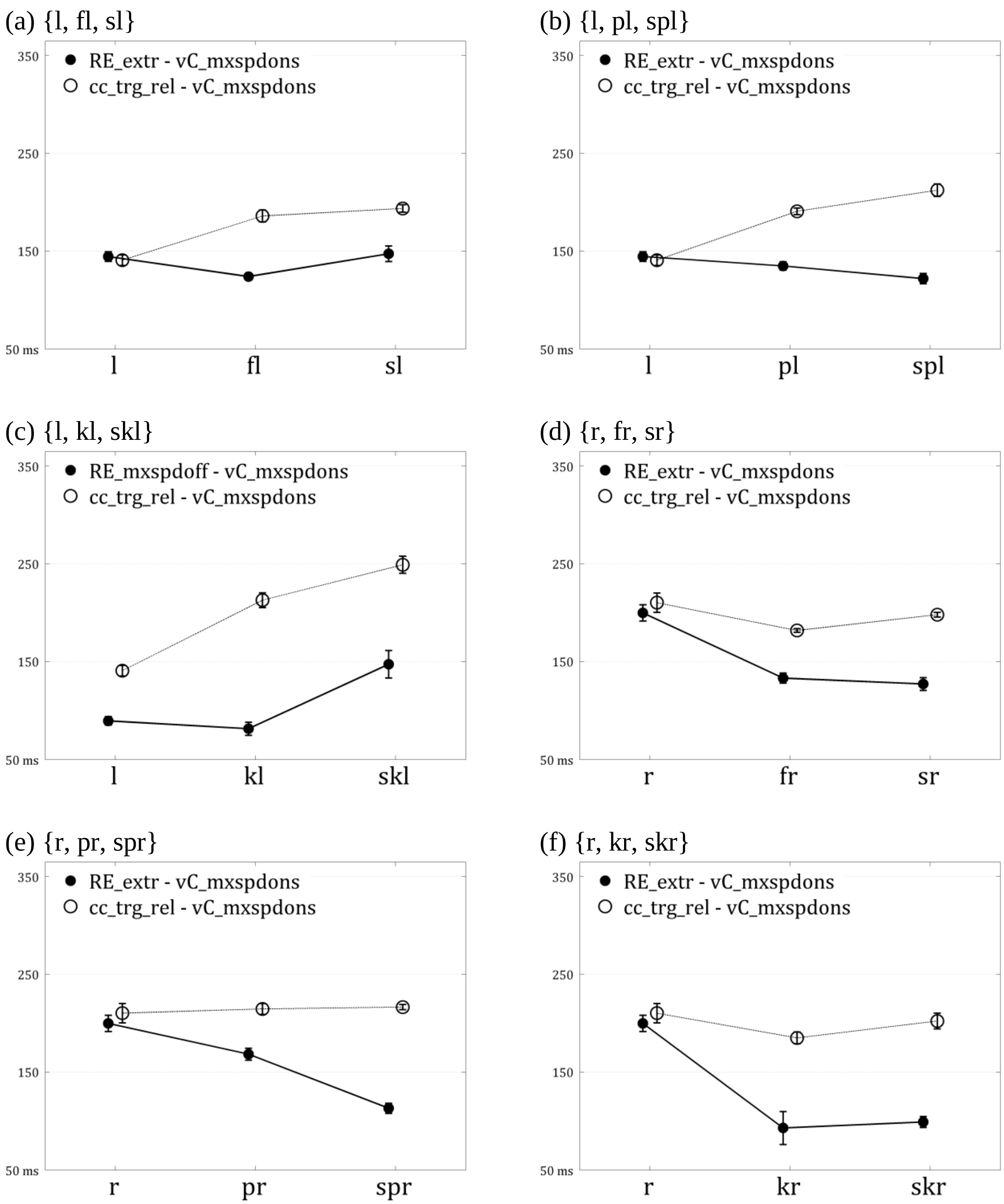
Evidence for complex timing of word-initial consonants has been observed in English by a number of previous studies, including Browman & Goldstein (1988), Honorof & Browman (1995), and Marin & Pouplier (2010). Our study aimed to replicate these results and extend them to previously unexamined non-occurring clusters. Many of our target stimuli were nonwords (see Appendix, Table A3), since we aimed to control the vowel and post-vocalic consonant across all stimuli. All of the stimuli consisted of (an) initial consonant(s) followed by /æts/. The clusters examined were {l, fl, sl, pl, kl, spl, skl}, {r, fr, sr ,pr, kr, spr, skr}, {f, sf, kf}, {k, sk, pk}, and {p, sp, kp}. Of these clusters, /kf/, /pk/, and /kp/ do not occur in the English lexicon, and /sf/ and /sr/ are rare or occur only in loanwords (e.g. *sphere* or *Srini*). We expected /kf/ and /sf/ to exhibit simplex timing, since obstruent-obstruent clusters are rare in English; in contrast, we expected /sr/ to pattern like other obstruent-/r/ clusters and exhibit complex timing. For /pk/ and /kp/ we expected simplex timing due to the non-occurrence of word-initial stop-stop clusters in English. We note that the speaker who participated in our study was phonetically trained and thus may have acquired non-native temporal organization for these rare or non-occurring clusters. In addition, the speaker was one of the co-authors and hence was aware of the purpose of the experiment.

For all responses, the anchor point was defined as the maximum speed of the onset of the post-vocalic /t/ (i.e. vC-mxspdons), identified using vertical displacement of the TT sensor. RE-lags were defined as extrema of the pre-vocalic consonantal gesture. Following Pouplier & Beňuš (2011), the horizontal movement of the TD was used to identify gestural landmarks associated with /r/, which exhibited a tongue retraction gesture in combination with a variable TT raising gesture. The TT raising gesture was not apparent in some clusters and hence not suitable for lag-based comparisons. Analysis of /l/ was more problematic: neither the TD nor TT provided a consistent plateau within some cluster groups. For c-center lags we illustrate in Fig. 6 both a first-order c-center (here the midpoint between LE-trg and RE-rel), and a second-order c-center, the midpoint of RE and LE c-centers.

Clusters with prevocalic /l/, shown in Fig. 6a-c, exhibit one of two patterns. For clusters involving a labial consonant,{fl, pl, spl}, we observed a decrease in RE-lag compared to the singleton /l/, which provides indirect evidence of complex timing; however, these are contradicted by increases in c-center measures which are of greater magnitude. For clusters involving a lingual articulation, {sl, kl, skl), there is an unexpected increase in both RE-lags and c-center lags relative to singleton /l/. This may be due to the confounding factor of lingual coarticulation, and hence no firm conclusions can be drawn from these comparisons.

Clusters with prevocalic /r/, shown in Fig. 6d-f, exhibit both indirect and direct evidence for complex timing. As predicted, /fr/ and /sr/ pattern similarly, exhibiting decreased RE-extr lag and relatively stable c-center lags compared to singleton /r/. The group {r, pr, spr} exhibits a decrease of the RE-lag as consonants are added, while the c-center remains relatively constant. The same holds for {r, kr, skr}, although the RE-lag between {kr, skr} did not differ.

Sibilant-initial clusters with prevocalic obstruents /f/, /p/, and /k/, shown in Fig. 6g-i, exhibit direct and indirect evidence for complex timing, as hypothesized. For {f, sf} the RE-lag decreased by a modest 20 ms with no change in the cc-lag. For {p, sp} the RE-lag decreased by about 40 ms with no substantial change in the cc-lag. For {k, sk} the RE-lag decreased by 25 ms, while the cc-lag increased by about 15 ms. Regarding the stop-obstruent clusters /kf/, /kp/, and /pk/, some interesting differences emerge. The comparisons {f, kf} and {p, kp} showed modest decreases in RE-lag, but a similar increases in cc-lag, which supports neither complex nor simplex timing. In contrast, {k, pk} appears to exhibit simplex timing, with a slight increase in RE-lag and more drastic increase in c-center lag.


(a) {l, fl, sl}
RE_extr - vC_mxspdons
cc_trg_rel - vC_mxspdons
350
250
150
50 ms
l
fl
sl
(b) {l, pl, spl}
RE_extr - vC_mxspdons
cc_trg_rel - vC_mxspdons
350
250
150
50 ms
l
pl
spl
(c) {l, kl, skl}
RE_mxspdoff - vC_mxspdons
cc_trg_rel - vC_mxspdons
350
250
150
50 ms
l
kl
skl
(d) {r, fr, sr}
RE_extr - vC_mxspdons
cc_trg_rel - vC_mxspdons
350
250
150
50 ms
r
fr
sr
(e) {r, pr, spr}
RE_extr - vC_mxspdons
cc_trg_rel - vC_mxspdons
350
250
150
50 ms
r
pr
spr
(f) {r, kr, skr}
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cc_trg_rel - vC_mxspdons
350
250
150
50 ms
r
kr
skr

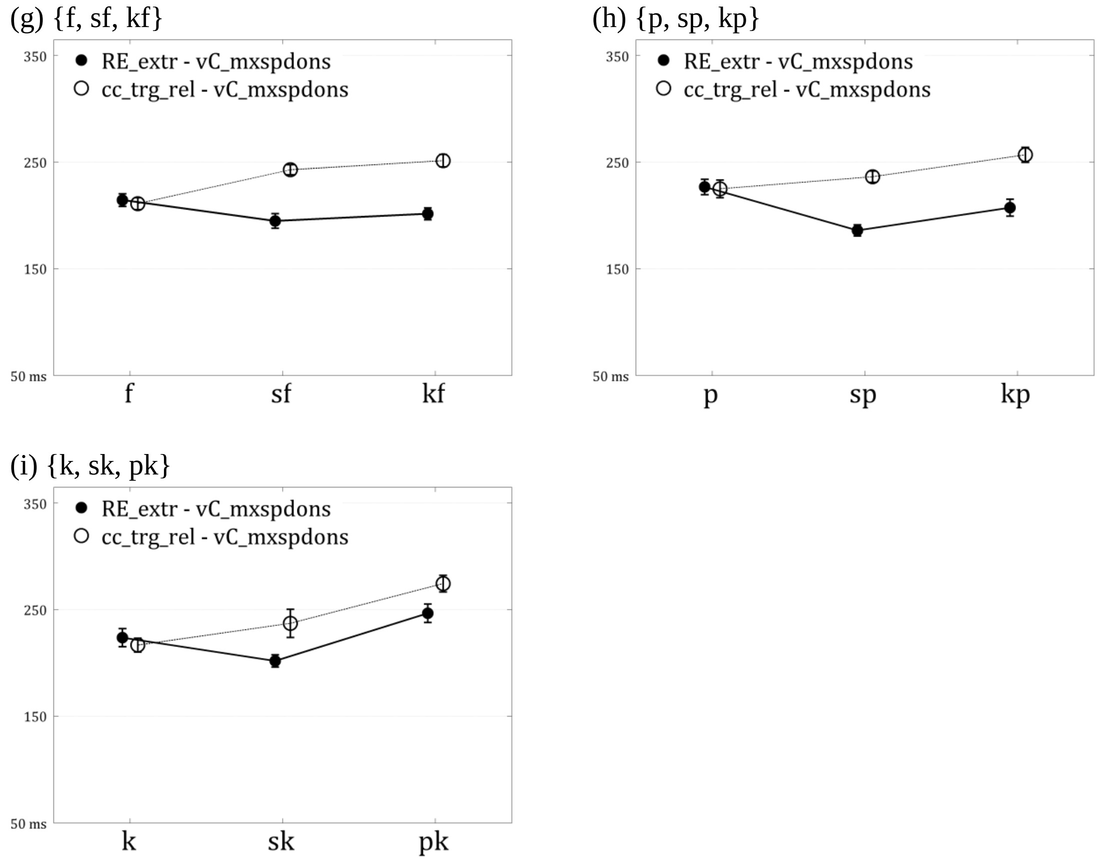


Figure 6. Right-edge and c-center lags for English word-initial clusters.

In sum, our English study replicated previous results: clusters with a prevocalic /r/ exhibited evidence for complex timing, and so did sC clusters. However, the results for stimuli involving prevocalic /l/ are not consistent with previous findings, as cc-lags were observed to increase in complex onsets. In examining articulatory trajectories from individual tokens, we have observed that this increase arises from a change in how the /l/ is articulated in clusters: the vertical displacement of the TT is more variable and often lower in magnitude in (C)C/l/ cluster. Our study also examined non-occurring stop-obstruent clusters /kf/, /kp/, and /pk/, and found that the dorsal-labial clusters differed from the labial-dorsal cluster: the former showed RE-lag decreases and comparable cc-lag increases, while the latter is more consistent with a simplex timing pattern. This raises the question of why the coronal-labial and labial-coronal obstruent clusters pattern differently. One possibility involves the corresponding back-front and front-back closure asymmetry. The release of a more posterior closure is subject to acoustic masking from a subsequently produced more anterior closure. In order to maintain perceptual recoverability of both gestures, they must be temporally overlapped less in back-front CC than in the front-back CC (Chitoran & Goldstein, 2002). This might be accomplished by using complex timing to shift the prevocalic consonant closer to the vowel; however, it seems equally likely that simplex timing could be used to shift the initial consonant further from the vowel. Hence the asymmetry observed in /kp/ vs. /pk/ coordination remains somewhat puzzling.

6 Results: Serbian

Complex onsets in Serbian have not been previously investigated using electromagnetic articulometry. Serbian has a rich set of possible onset clusters constrained by two main principles:

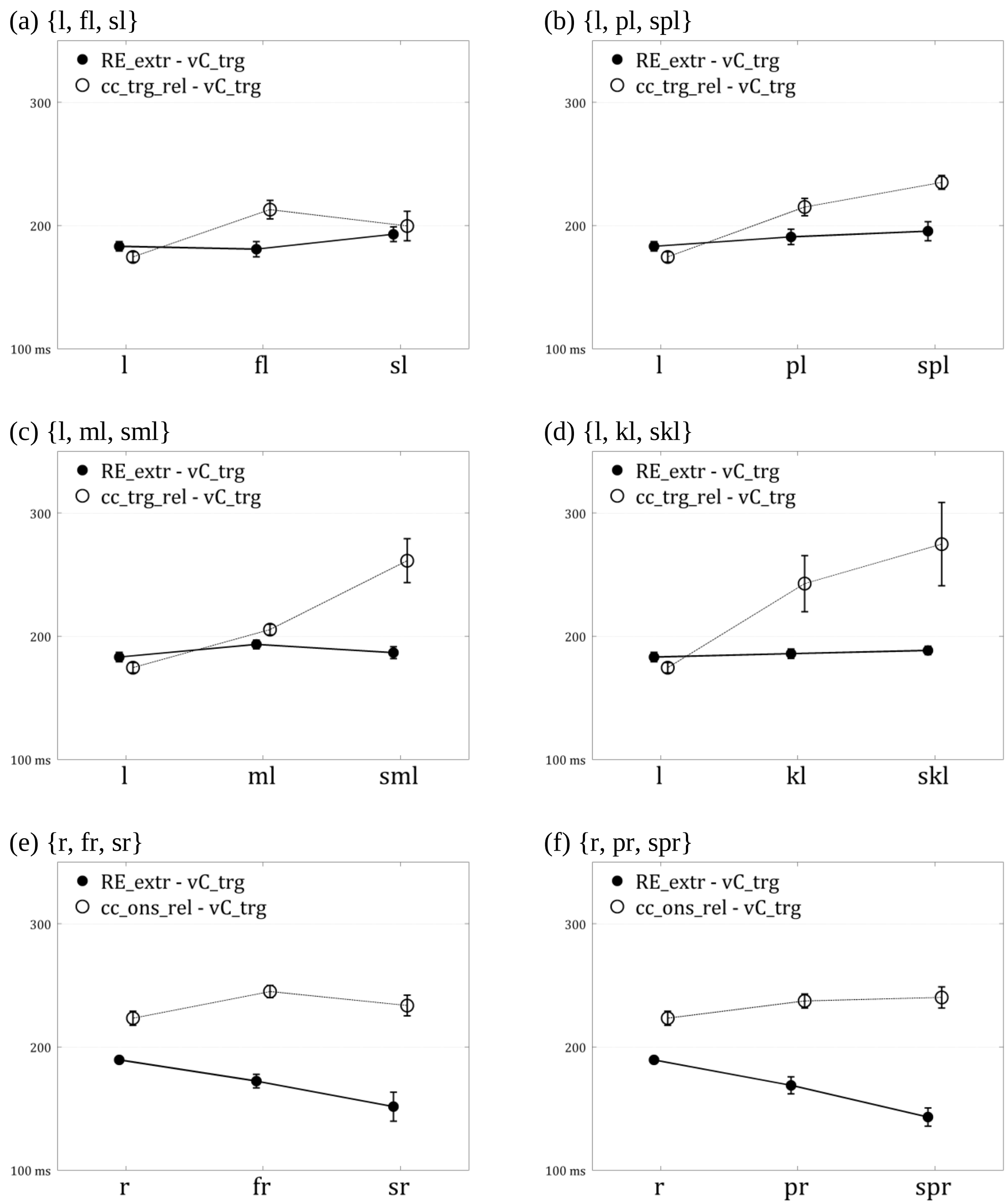
obstruent clusters must agree in voicing specification, and there are no sonority reversals among the major classes (thus sonorant-obstruent clusters are not permitted). Sonority plateaus are allowed (e.g., /pt/, /sx/, /mn/, /ml/), and nasals and liquids are permitted as the second member of a complex onset (e.g., /km/, /kl/, /kr/). Clusters of up to three consonants are permitted. We hypothesized that Serbian word-initial consonant clusters conforming to these phonotactic constraints would exhibit evidence for complex timing, whereas non-occurring sequences /kf/, /kp/, and /pk/ would exhibit simplex timing.

Our stimuli (Appendix, Table A4) consist of mostly nonwords of the form (C)(C)C/ata/, and hence the vowel and post-vocalic consonant were identical across stimuli. The clusters tested were {l, fl, sl, pl, spl, ml, sml, kl, skl}, {r, fr, sr, pr, spr, mr, smr, kr, skr}, {s, ps, ks}, {f, sf, kf}, {p, sp, kp}, and {k, sk, pk}. All stimuli were disyllabic. The speaker was instructed to produce them with penultimate stress and with a short falling accent on the stressed vowel, which is the default prominence pattern in Serbian. For all responses, the anchor point was defined as the target of the onset of the post-vocalic /t/ (i.e. vC-trg), identified using vertical displacement of the TT sensor. RE-lags were defined as extrema of the pre-vocalic consonantal gesture. As in our analysis of English, the horizontal movement of the TD was used to identify gestural landmarks associated with /r/, which exhibited a tongue retraction gesture in combination with a more variable TT raising gesture (cf. also Pouplier &Beňuš, 2011). Landmarks of /l/ were identified with vertical displacement of the TT.

In contrast to our hypotheses, clusters with prevocalic /l/ (Fig. 7a-d) exhibited evidence for simplex timing: RE-lag measures were relatively unchanging across clusters and cc-lags increased in complex clusters compared to singletons. We note, however, that as with other languages in our study, /l/ brings challenges for defining articulatory landmarks consistently across stimuli. The TT gesture of /l/ is subject to a substantial degree of reduction in clusters, and due to the laterality of the constriction, the TT sensor does not track the maximally displaced portion of the tongue.

Clusters with prevocalic /r/ (Fig. 7e-h) exhibited indirect evidence for complex timing (decrease in RE-lag measures), as predicted. However, the indirect evidence was not always corroborated by direct evidence. In {r, fr} RE-lag decreased by about 20 ms, yet there was a similar increase in cc-lag. In {r, sr}, the direct and indirect evidence were more consistent: RE-lag decreased by about 45 ms, while cc-lag was about the same. In {r, pr}, RE-lag decreased by 25 ms, while cc-lag increased by a modest 10 ms. Yet the comparison {pr, spr} showed a 30 ms decrease in RE-lag and no change in cc-lag, providing both indirect and direct evidence for complex timing. A similar pattern was observed for {r, mr, smr}, although the cc-lag of /smr/ increased by about 25 ms relative to /r/ and /mr/. In the comparison across {r, kr, skr}, decreases in RE-lag indicative of complex timing are contradicted by similar increases in cc-lag. However, we note that coarticulation between the dorsal /k/ and coronal /r/ appears to be responsible for making /r/ landmarks less robust and hence the cc-center measurements in Fig. 7h are more variable.

Contrary to our hypotheses, clusters with prevocalic /s/ (Fig. 7i) exhibited evidence for simplex timing, with relatively stable RE-lag measures and increasing cc-lags. The results are more ambiguous for prevocalic /f/ and /p/ clusters (Fig. 7j-k). For {f, sf, kf}, the complex cluster RE-lags decrease by 20 ms, while the cc-lags increase by about the same amount. For {p, sp, kp}, the RE-lags decrease by a modest 10-15 ms, and the cc-lags increase by about 25 ms. Neither of these patterns provides strong evidence for or against complex timing. Only in the {k, sk, pk} comparison do both types of lags provide converging evidence for complex timing: the RE-lag of complex clusters decreases by about 25 ms, while the cc-lags are nearly constant across clusters. For /pk/, the evidence for complex timing contradicts our hypothesis, which predicted simplex timing on the basis that this cluster does not occur in Serbian.


(a) {l, fl, sl}
RE_extr - vC_trg
cc_trg_rel - vC_trg
300
200
100 ms
l
fl
sl
(b) {l, pl, spl}
RE_extr - vC_trg
cc_trg_rel - vC_trg
300
200
100 ms
l
pl
spl
(c) {l, ml, sml}
RE_extr - vC_trg
cc_trg_rel - vC_trg
300
200
100 ms
l
ml
sml
(d) {l, kl, skl}
RE_extr - vC_trg
cc_trg_rel - vC_trg
300
200
100 ms
l
kl
skl
(e) {r, fr, sr}
RE_extr - vC_trg
cc_ons_rel - vC_trg
300
200
100 ms
r
fr
sr
(f) {r, pr, spr}
RE_extr - vC_trg
cc_ons_rel - vC_trg
300
200
100 ms
r
pr
spr

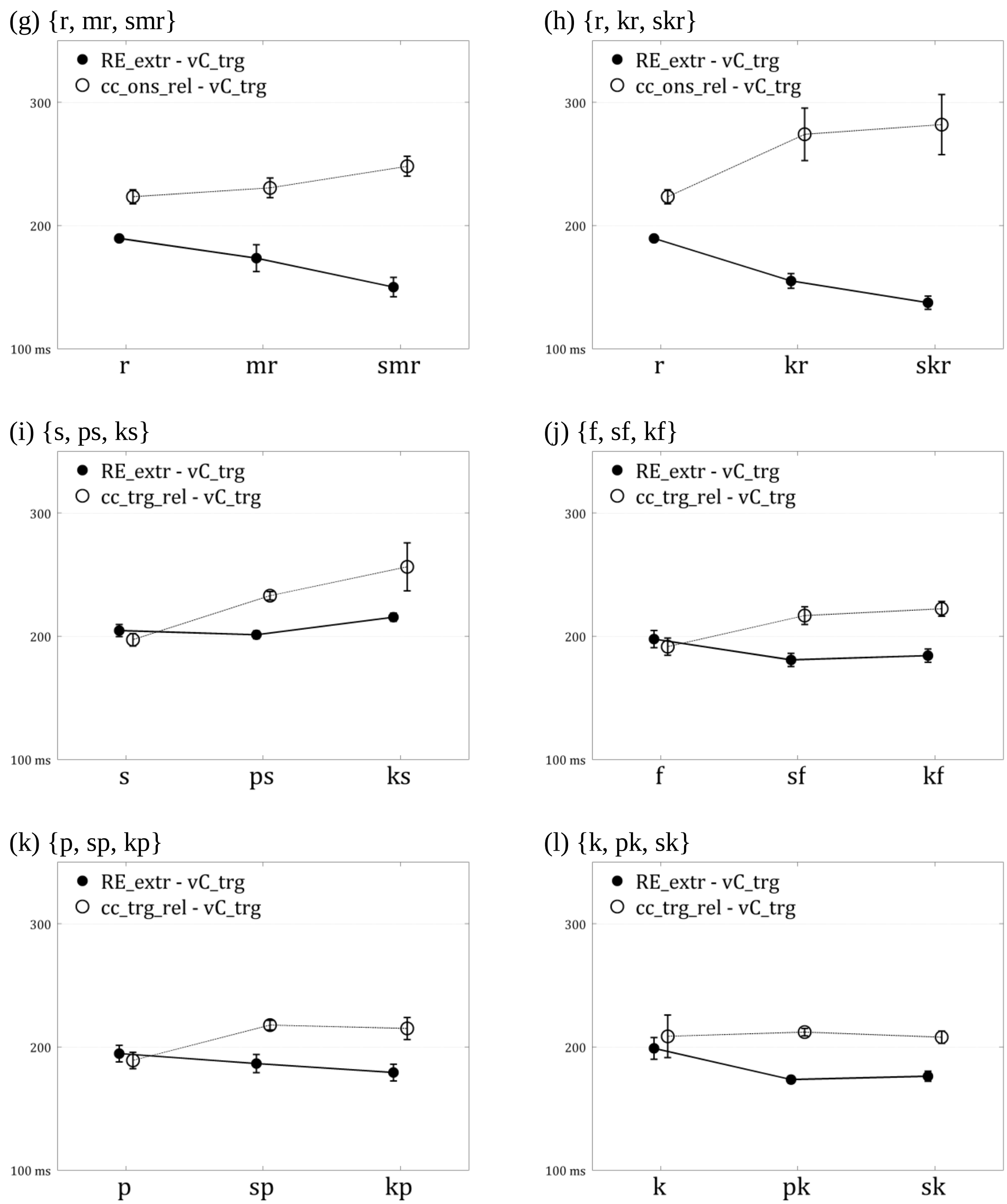


Figure 7. Right-edge and c-center lags for Serbian word-initial clusters.

7 Results: Hebrew

Complex onsets in Modern Israeli Hebrew have not been previously investigated using electromagnetic articulometry. Modern Hebrew contains a large set of possible consonant clusters; our hypotheses in this case are derived from considerations of historical developments. Biblical Hebrew did not allow initial consonant clusters: a schwa was epenthesized between consonants and this still occurs in Modern Hebrew in certain cases, discussed below. When Hebrew was revived, the epenthesis rule was eliminated, possibly due to the phonotactic complexity allowed in native languages of speakers who were responsible for the revival (Bolozky, 2004). Clusters are regularly created by the morphology, which is traditionally described as applying templatic patterns to the consonants of a root. Thus, for example, the masculine plural is formed as /$C_1C_2aC_3$/ + /im/ and so for the word /klv/ "dog", the plural is /klavim/.

Hebrew disallows clusters which violate the Obligatory Contour Principle by matching in place and manner of articulation; when morphological structure would create these, they are divided by an epenthetic /e/. In some dialects, consonant clusters that would constitute a sonority reversal or plateau also get broken up by epenthetic /e/. Clusters starting with guttural consonants get broken up by /a/, both word-initially and internally, and an /e/ is usually epenthesized in clusters with a uvular/velar fricative /x/ (< */χ/, /k/) or second member /h/ or /ʔ/. An /i/ is epenthesized in CCC clusters after the initial consonant (Schwarzwald, 2001). Furthermore, in Modern Hebrew, word-medial onsets very infrequently have clusters, while word-initial clusters are common. Based on these observations, we hypothesize that Hebrew exhibits simplex timing in word-initial clusters.

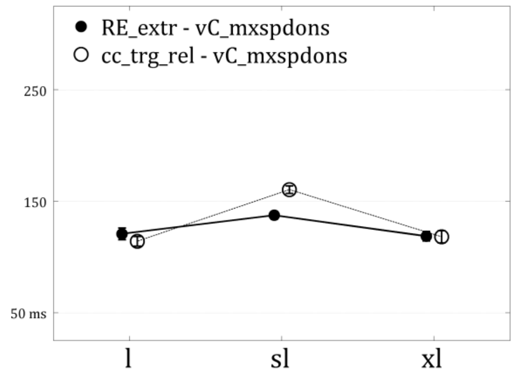
Our stimuli (Appendix, Table A5) consisted of non-words of the form /(C)Catim/, which can be interpreted as plurals resulting from the common plural formation /$C_1C_2aC_3$/ + /im/. The cluster groups we analyzed were {l, fl, sl, xl, pl, kl, spl, skl}, {r, fr, sr, xr, pr, kr, spr, skr}, {k, sk, pk, tk}, {t, xt, pt, kt}, {p, sp, tp, kp}, {s, xs, ps, ks}, and {x, sx, px, tx, kx}. All of these are licit clusters; however, /x/-initial clusters, C/p/, and CCC are uncommon and mostly occur in borrowed words. The speaker produced the stimuli with word-initial stress, the default pattern in Hebrew. For all responses, the anchor point was defined as the maximum speed of the onset of the post-vocalic /t/ (i.e. vC-mxspdons), identified using vertical displacement of the TT sensor. RE-lags were defined as target of the pre-vocalic consonantal gesture (RE-trg). Our speaker did not produce a consistent upward vertical displacement of the TT for /r/, nor a horizontal retraction of the TD. This may not be surprising, given that in some dialects /r/ behaves like a uvular approximant [ʁ] (Kreitman, 2008). Instead, we observed that the /r/ was associated with a downward extremum in the vertical position of the TT sensor, which may accompany uvular constriction or may reflect a bunched-/r/ configuration; hence we defined the downward extremum of the TT as a landmark for /r/. We furthermore found that the vertical movement of the TD sensor gave us the most robust representation of the /l/ articulation. All other consonants were landmarked using the standard articulators.

Some clusters with prevocalic /l/ exhibit evidence for simplex timing, as predicted. For {l, sl, xl} (Fig. 8a), RE-lags were relatively constant across clusters. The same was true for {l, pl} (Fig. 8b), although /spl/ showed an unexpected increase in both RE- and cc-lags. Likewise, clusters involving /kl/ (Fig. 8c) exhibited an anomalous increase in both RE- and cc-lags. This may be due to changes in the articulation of /l/ in clusters, which may depend upon whether another segment with lingual articulation is present.

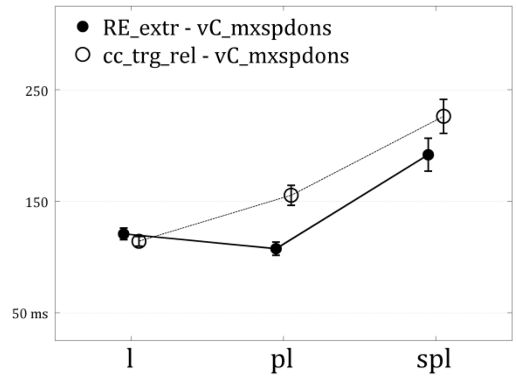
Clusters with prevocalic /r/ exhibited a complex timing pattern, in contrast to our hypotheses. For {r, sr, xr, pr, kr} (Fig. 8d-f) both indirect and direct evidence was observed: RE-lags decreased in complex clusters, while cc-lags were relatively stable. For the CCC clusters /spr/ and /skr/ (Fig. 8e-f), the evidence is more ambiguous: RE-lag in /spr/ decreased slightly relative to /pr/, while the cc-lag increased more substantially; likewise, cc-lag increased in /skr/ relative to /kr/, and the RE-lag remained about the same. One possible interpretation of this result is that initial /s/ in a triconsonantal cluster exhibits simplex timing.

Clusters with prevocalic obstruents showed mostly a simplex timing pattern, as hypothesized. For the prevocalic fricatives /s/ and /x/ (Fig. 8g-h), RE-lags were fairly stable across singletons and cluster for /s/ and /x/, while cc-lags increased more substantially. The one exception to this result is in /kx/, where RE-lag increased substantially, although this pattern is likely an artifact of coarticulation due to the shared place of articulation between /k/ and /x/. For the prevocalic stops /p/ and /k/ (Fig. 8i-j), RE-lags were constant or decreased slightly in the complex clusters, and there was a relatively larger increase in cc-lags.

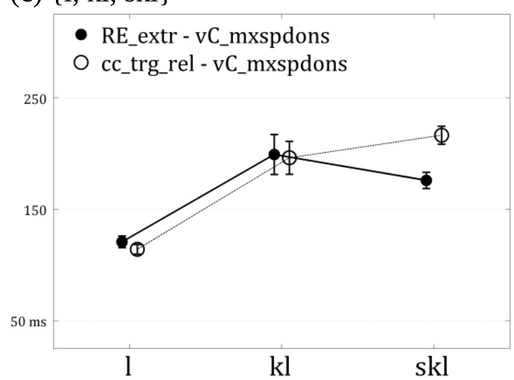
(a) {l, sl, xl}



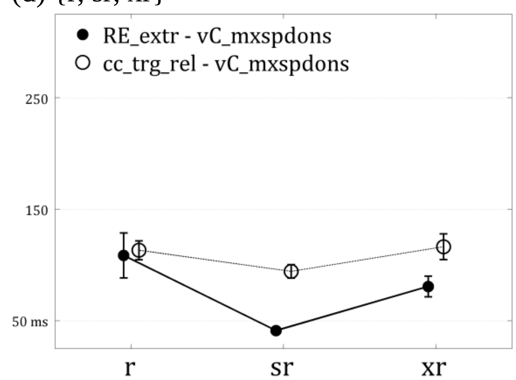
(b) {l, pl, spl}



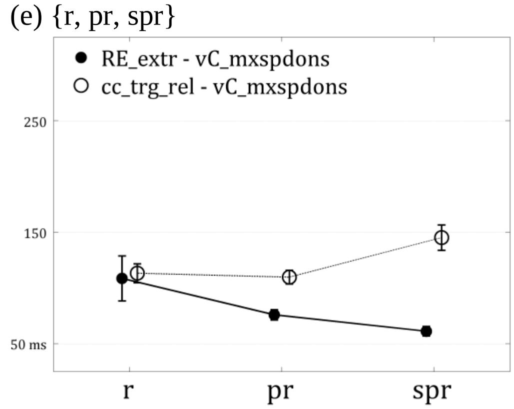
(c) {l, kl, skl}



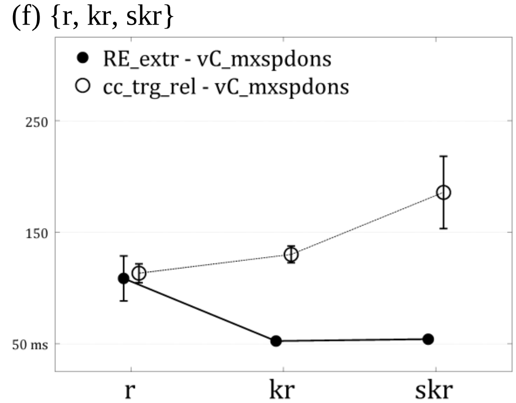
(d) {r, sr, xr}



(e) {r, pr, spr}



(f) {r, kr, skr}



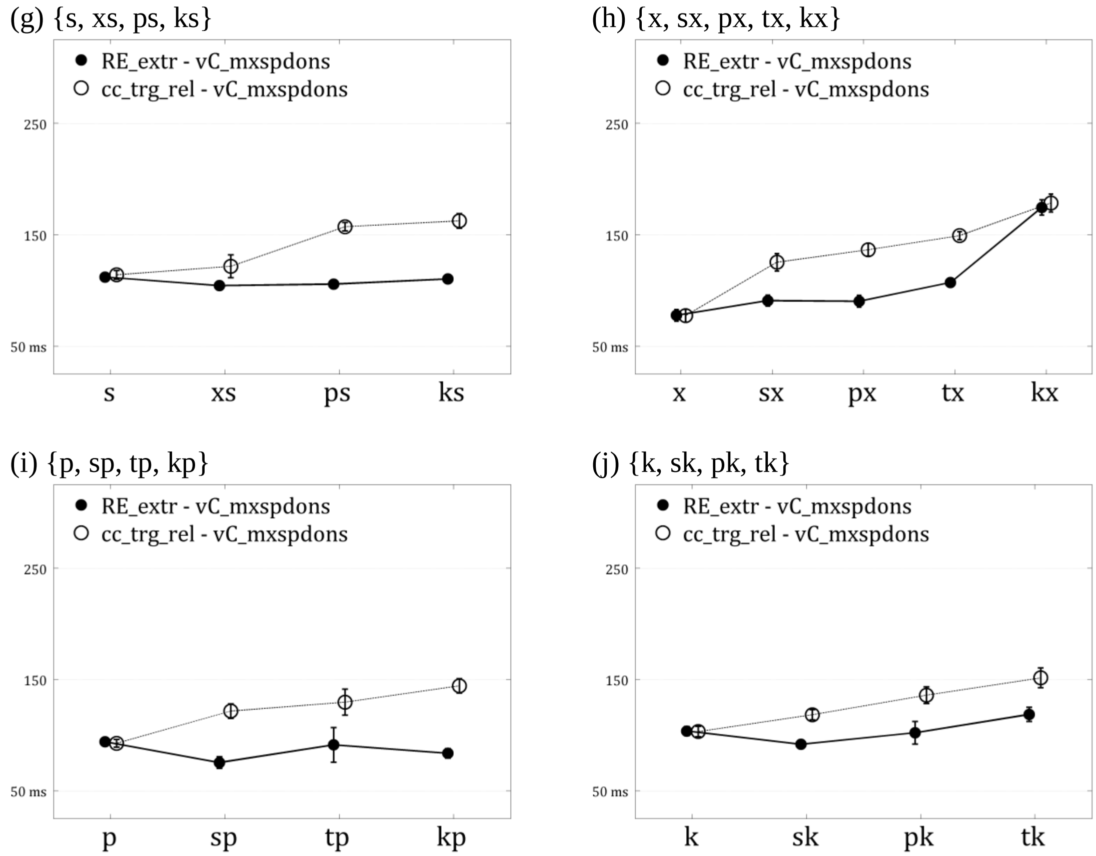


Figure 8. Right-edge and c-center lags for Hebrew word-initial clusters.

In sum, our investigation of Hebrew largely confirmed our hypotheses of simplex timing, although prevocalic /r/ clusters were an exception. Clusters with prevocalic /l/ mostly exhibited stable RE-lags, although dorsal C/l/ clusters and CC/l/ clusters did not. Clusters with prevocalic stops and fricatives also exhibited evidence for simplex timing, with relatively constant RE-lags. The notable exception was clusters with prevocalic /r/, in which RE-lags decreased and cc-lags were more stable. Given that complex word-initial clusters are a relatively recent development in Modern Hebrew, one possibility is that complex coordination of C/r/ clusters is an innovation. This constitutes evidence that coordinative timing can be segment-specific.

8 Conclusion

We conducted investigations of articulatory timing in five languages: Italian, Montreal French, English, Serbian, and Hebrew, with the aim of identifying complex or simplex timing of consonantal gestures relative to the following vowel. The results of our replication/extension studies (Italian, Montreal French, English) are to a partial extent consistent with prior work, and the results of our studies of previously unexamined languages (Serbian, Hebrew) provide original data on the basis of which complex/simplex timing can be attributed to these languages. However, in both types of studies we observed a number of patterns which raise both methodological and theoretical questions which should be addressed in theoretical studies.

In both of the original studies, we observed that evidence for simplex or complex timing depended upon the prevocalic consonant. For instance, in Hebrew, where we hypothesized simplex timing, we generally observed simplex timing patterns for all clusters except those with prevocalic /r/. In Serbian we hypothesized complex timing, but for prevocalic /l/ and /s/ clusters we observed patterns more consistent with simplex timing. Prevocalic /f/ and /p/ clusters provided ambiguous evidence for complex timing, while C/k/ clusters showed corroborating indirect and direct evidence for complex timing.

Our replication studies were only partly consistent with prior work. In English, clusters with a prevocalic /r/ exhibited evidence for complex timing, and so did sC clusters. The patterns were mostly consistent with previous studies of English which have provided evidence for complex timing. In contrast, our results for English prevocalic /l/ clusters were suggestive of simplex timing, although there are several reasons specific to /l/ (discussed below) which may call these findings into question. In Montreal French, our results diverge markedly from a prior study of Continental French. We hypothesized that Montreal French would exhibit complex timing based on data from Kühnert et al. (2006), yet we predominantly observed simplex timing patterns in prevocalic /l/, /f/, /p/, and /t/. The divergence between our results and the prior study suggest that the dialect of Montreal French may differ from Continental French with regard to the coordination of word-initial consonant clusters. However, we note that the comparison between studies is limited to prevocalic /l/ clusters and articulatory landmarking of /l/ may be less robust. Kühnert et al. (2006) also examined prevocalic /n/ clusters, finding evidence for complex timing. Our Montreal French data are original in examining less frequent prevocalic /f/, /p/, and /t/ clusters, in which we observed simplex timing. Hence we conclude that clusters with prevocalic obstruents exhibit simplex timing in Montreal French. In Italian, we encountered difficulty in attaining reliable landmarks for both prevocalic /l/ and /r/, resulting in relatively high variability of some lag measures involving those consonants. We also favored real-word stimuli resulting in sets of clusters for which vowel and/or post-vocalic consonants were not identical. These factors complicate our analysis and in some cases preclude any firm conclusions. Prior work by Hermes et al. (2006) supports a hypothesis of complex timing in Italian, with the exception of /s/C(C) clusters in which the /s/ appears not to participate in a complex timing relation with the following vowel. This specific finding was replicated by our study for the /spr/, /zbr/ vs. /pr/ comparison and for the /sfr/ vs. /fr/ comparison: RE-lags did not differ between these clusters.

In conducting analyses of data, we observed for all languages that lag measures involving prevocalic /l/ were often more variable and that /l/ gestural landmarks were difficult to robustly identify, particularly in clusters with another lingual articulation. This is evidenced by the fact that it was necessary to use alternative representations of the /l/ articulatory trajectories in some languages. Whereas in Italian, Montreal French, and Serbian we were able to use a vertical maximum of the TT to identify the /l/ gesture, the absence of a regular vertical displacement associated with /l/ forced us to use alternatives: in English we used a horizontal anterior maximum of the TD sensor, and in Hebrew we used a vertical maximum of TD. In examining articulatory trajectories from individual tokens with prevocalic /l/, we have observed that the vertical displacement of the TT is more variable and often lower in magnitude in (C)C/l/ clusters than as a singleton /l/. This appears to be related to the propensity for the TT gesture of /l/ to reduce in clusters and to be influenced by coarticulation with other lingual gestures. Another factor complicating interpretation of /l/ gestural landmarks is that the TT sensor is located in the mid-sagittal plane and hence does not reflect the portion of the tongue that is maximally displaced in lateral gestures.

An important contribution of our study is to highlight the distinction between indirect and direct evidence for complex timing. Whereas a decrease in RE-lag in word-initial clusters provides indirect evidence, the presence of a stable c-center provides more direct evidence. As shown in the language-specific analyses above, the two forms of evidence are often not in agreement. According to the theory of articulatory phonology, complex organization emerges because gestural planning systems associated with a complex onset are specified to be in-phase coordinated with the vocalic gesture, and the stability of the c-center derives from an assumption of equal consonant-vowel coupling forces competing with an anti-phase coupling force between consonants. Hence this model predicts that in onsets with complex organization there should be a midpoint (c-center) of the pre-vocalic gesture(s) that is stably timed relative to a following vocalic anchor.

Many studies (cf. section 1.1) have relied on only indirect evidence, i.e. an associated decrease of RE-lag in complex onsets, but our results indicate that this RE-lag pattern can be contradicted by comparable increases in cc-lags. One possible explanation for this is that word-initial consonants may be asymmetrically coupled to the vocalic gesture, in which case the c-center would need to be redefined as a weighted midpoint of gestural landmarks. Another possibility is that compression of articulatory gestures skews lag measures and hence confounds the general diagnostics for simplex/complex timing. Indeed, Shaw et al. (2011) show that by varying degrees of vowel and consonantal compression, languages with simplex organization can exhibit patterns associated with complex timing, and vice versa. In that case, the diagnosis of simplex/complex timing requires sampling a range of segmental compressions, which may be accomplished by experimentally controlling speech rate or prosodic influences.

In conclusion, our studies have provided new data on articulatory timing in word-initial consonants. Hebrew exhibits simplex timing in most clusters, with the exception of prevocalic /r/ clusters, which may be an innovation. Serbian appears to exhibit complex timing in most clusters, with the possible exception of prevocalic /s/ clusters. Montreal French exhibits simplex timing in clusters with prevocalic obstruents, which have not previously been studied from the current perspective. We replicated the finding that in Italian /s/ exhibits simplex timing in /s/C(C) clusters and replicated complex timing in English clusters. We found that our results often diverged from our predictions in prevocalic /l/ clusters, and to account for these discrepancies we have identified several complications in analyzing /l/ for the purposes of characterizing timing. Finally, our results show that indirect and direct evidence for complex timing are not always consistent; this speaks to the need to distinguish between both forms of evidence in analyses of timing, and suggests that future empirical investigations explore the effects of compression on the timing of word-initial consonants.

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Appendix

Table A1. Italian word list

CV	gloss	CCV	gloss	CCCV	gloss
fila	*line*	flirta	*flirt (3sg)*	scriba	*scribe*
lina	*proper name*	frisa	*nonce*	sclera	*going crazy*
pina	*proper name*	plina	*pline*	sprima	*nonce*
rima	*rhyme*	prima	*first*	sblocca	*release (3sg)*
sita	*situated*	psiche	*psych*	sbriga	*hurry up (3sg)*
vita	*life*	sfila	*unthread (3sg)*	sfrigola	*sizzle (3sg)*
china	*bend (3sg)*	schifa	*disgusting*	sgrida	*yell at (3sg)*
		spina	*spine*		
		sbircia	*peek at (3sg)*		
		sghignazza	*guffaw (3sg)*		
		slitta	*sleigh*		
		sradica	*uproot (3sg)*		
		svita	*unscrew (3sg)*		
		crine	*horsehair*		
		clima	*climate*		

Table A2. Montreal French word list

CV	gloss	CCV	gloss
fatal	*fatal*	scalpel	*scalpel*
fatigue	*tired*	scalène	*scalene*
cathare	*Cathar*	flatter	*to pet*
cathode	*cathode*	flacon	*bottle*
latin	*latin*	classique	*classical*
latex	*latex*	classeur	*filing cabinet*
patate	*potatoe*	plateau	*plateau*
patère	*peg*	platine	*platinum*
satire	*satire*	slovaque	*Slovak*
satin	*satin*	slovène	*Slovenian*
tatou	*armadillo*	spatule	*spatula*
tatar	*Tatar*	spatial	*spatial*
		psychose	psychosis
		psyché	psyche
		pterodactyl	pterodactyl
		spherique	sphere
		sphyncter	sphincter

Table A3. English word list

CV	CCV	CCCV
fats	flats	sclats
cats	frats	scrats
lats	kfats	splats
pats	clats	sprats
rats	kpats	
sats	crats	
	ksats	
	pfats	
	pkats	
	plats	
	prats	
	psats	
	sfats	
	scats	
	slats	
	spats	
	srats	

Table A4. Serbian word list

CV	CCV	CCCV
rata	mrata	smrata
lata	frata	sprata
mata	srata	skrata
fata	prata	smlata
sata	krata	splata
pata	mlata	sklata
	flata	
	slata	
	plata	
	klata	
	pmata	
	psata	
	pfata	
	pkata	
	kmata	
	ksata	
	kfata	
	kpata	
	smata	
	sfata	
	spata	
	skata	

Table A5. Hebrew word list

CV		CCV		CCCV	
fatim	פַטִים	pkatim	פְּכַּטִים	sklatim	סְכְּלַטִים
katim	כַּטִים	tkatim	טְכַּטִים	splatim	סְפְּלַטִים
latim	לַטִים	skatim	סְכַּטִים	skratim	סְכְּרַטִים
patim	פַּטִים	platim	פְּלַטִים	spratim	סְפְּרַטִים
ratim	רַטִים	klatim	כְ◌ְ◌ּלַטִים		
satim	סַטִים	slatim	סְלַטִים		
tatim	טַטִים	xlatim	ךְלַטִים		
xatim	ךַטִים	tpatim	טְפַּטִים		
		kpatim	כְ◌ְ◌ּפַּטִים		
		spatim	סְפַּטִים		
		pratim	פְּרַטִים		
		kratim	כְ◌ְ◌ּרַטִים		
		sratim	סְרַטִים		
		xratim	ךְרַטִים		
		psatim	פְּסַטִים		
		ksatim	כְ◌ְ◌ּסַטִים		
		xsatim	ךְסַטִים		
		ptatim	פְּטַטִים		
		ktatim	כְ◌ְ◌ּטַטִים		
		xtatim	ךְטַטִים		
		pxatim	פְּךַטִים		
		txatim	טְךַטִים		
		kxatim	כְ◌ְ◌ּךַטִים		
		sxatim	סְךַטִים		

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